Effect of Temperature on MEMS Vibratory Rate Gyroscope

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Abstract—We report the temperature dependence of the JPL/Boeing MEMS second generation Post Resonator Gyroscopes and determine the effect of hysteresis over the range 35°C to 65°C. The results indicate a strong linear dependence of the drive frequency and sense frequency with temperature of 0.093Hz/°C and AGC bias voltage with temperature of 13mV/°C. The results also indicate a significant time lag of the gyroscope of these quantities when responding to external temperature variations but determined no hysteresis exists in the drive frequency, sense frequency, and AGC bias. Both the time-frequency and time-bias voltage relationships are of the form y = A+B*exp(-t/T) where A is an offset parameter in Hertz and Volts respectively and B depends on the magnitude of the temperature variation. [1,2]

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1. INTRODUCTION

MEMS Post Resonator Gyroscopes (PRGs) are under development at the Jet Propulsion Laboratory to provide future NASA missions with a low cost, navigation grade, reduced mass, and low-power consumption inertial measurement unit [1]. The performance of this device is roughly an order of magnitude better than that of other competing MEMS-based gyroscopes, and is comparable in performance to optical gyroscopes. Gyroscope stability and behavior over variations in temperature is crucial to its long-term performance in all NASA mission conditions. This research is being done in conjunction with others in order to develop an integrated Inertial Measurement Unit (IMU) for the MEMS microgyro that can auto-tune using evolutionary algorithms [7], [8].

The PRG is a MEMS analogue to the classical Foucault pendulum. A Pyrex post anodically bonded to a silicon plate is driven into a rocking mode by sinusoidal actuation via electrodes beneath the plate. In a rotating reference frame the post is coupled to the Coriolis force, which exerts a tangential "force" on the post. Another set of electrodes beneath the device sense this component of motion. The voltage that is required to null out this motion is directly proportional to the rate of rotation to which the device is subjected.

Competing designs such as spinning-mass gyroscopes are typically orders of magnitude larger, more massive, and power consumptive, so there is a great incentive among the aerospace community to develop lighter, more compact and power-efficient gyroscopes. Optical gyroscopes such as Fiber Optic Gyros (FOGs) and Ring Laser Gyros (RLGs)

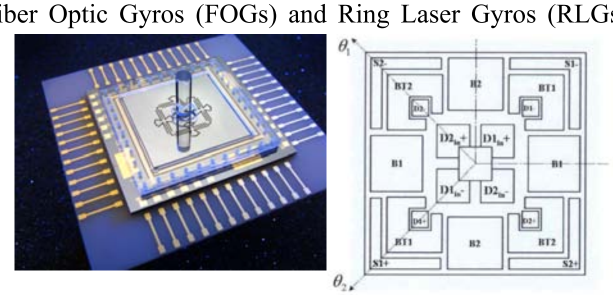

Figure 1. A representative picture of the instrumented MEMS gyro and corresponsing diagram of the 16-segmented electrode.

are also large, power consumptive and expensive; in addition, FOGs suffer performance degradation when exposed to radiation due to optical fiber darkening, while RLGs suffer from laser life issues [6]. This adds incentive to develop the MEMS devices in order to produce a navigation-grade gyroscope for spaceflight with the form-factor available with these devices. The end result of using the microgyro in these non-conventional environments will reduce size, mass and power while maintaining control of the remote system. Typical applications that would benefit

[1] 0-7803-8870-4/05/$20.00©2005 IEEE
[2] IEEEAC paper #1283, Version 5, Updated January 10, 2005

from this technology include: inertial spacecraft navigation to complement a star tracker or sun sensor, integration of the device in a planetary rover or lunar or planetary sample return missions that have a premium on weight because of the cost of lifting mass off the remote surface, the detection of angular rotation in all axes of a robotic arm.

While there have been several MEMS gyroscopes developed [3] [4] (see [5] for a comprehensive review), the performance of these devices for spaceflight to date has been inadequate due to large bias stabilities (> 1 deg/hr) resulting in zero-rate drift. The PRG has demonstrated vastly improved ambient bias stability (0.1 deg/hr) over competing MEMS designs; however, this performance must still be demonstrated over temperature. A previous study on the effects of temperature on an earlier design of the PRG has been reported, but there has been a major revision in the architecture of the baseplate both in size and in the number of capacitive segments since that work [2]. The newer version of the gyroscope can be seen in Figure 1, where the 16 capacitive segments are visible. This paper presents the results of a study of the temperature dependence for this next-generation design. In particular, this study was performed to determine if the response to temperature exhibits a hysteretic behavior. This is of paramount importance because correction for hysteresis greatly complicates the readout and more importantly reduces the overall sensitivity of the Inertial Measurement Unit (IMU) as a system. This paper is organized so that a brief introduction to PRGs is shown in Section 2, followed by a description of the test setup in Section 3. The results are shown in Section 4 and discussed in Section 5.

2. MEMS POST-RESONATOR GYROSCOPE

Post Resonator Gyroscopes (PRGs) employ Coriolis force coupling between two degrees of freedom in a vibratory mass internal to the sensor. This vibratory mass is fabricated to exhibit two natural frequencies of vibration f_1 and f_2, one for each degree of freedom. An automatic gain control (AGC) loop vibrates the gyroscope in the drive axis direction (θ_1 in Figure 2) at its resonance frequency f_1. Under rotation, a portion of the vibratory energy in the θ_1 direction is transferred to the θ_2 direction, or sense direction, at frequency f_2 via coriolis coupling. A force rebalance loop (FRB) in the closed-loop controller detects the transferred motion in the θ_2 direction as a sinusoidally-varying voltage due to the changing capacitance between the vibratory mass and electrodes on the base electroplate. The controller then applies force to dampen the vibration in the sense direction. The magnitude of this damping signal in the sense direction is proportional to the rate of rotation and found through demodulating and DC filtering with a sensed copy of the drive signal.

The precision of the gyroscope depends on the accuracy of

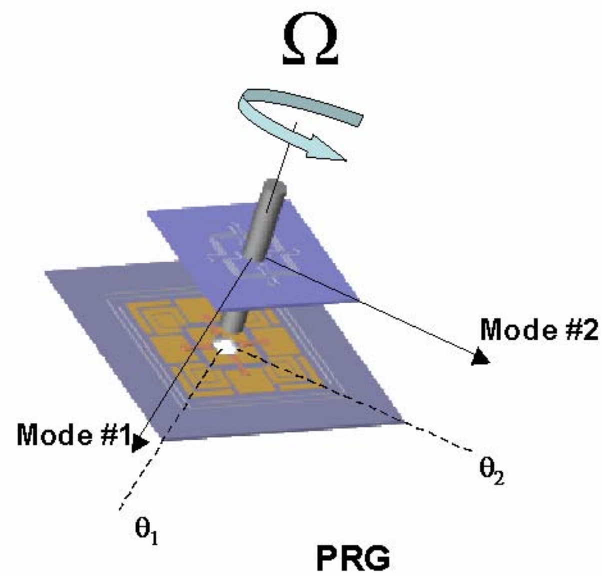

Figure 2. A schematic drawing of the dynamics of a Post-Resonator Gyroscope.

the AGC loop and FRB loop to produce stable and correct outputs over temperature and time. This study was performed by monitoring the AGC loop frequency (drive frequency), the FRB loop frequency (sense frequency), the AGC force bias (needed to keep the gyroscope mass vibrating at constant amplitude and phase), and the rotational rate bias as the temperature of the gyroscope is adjusted. Experiments were conducted with a three-hour sampling time per temperature and repeated to search for a hysteresis.

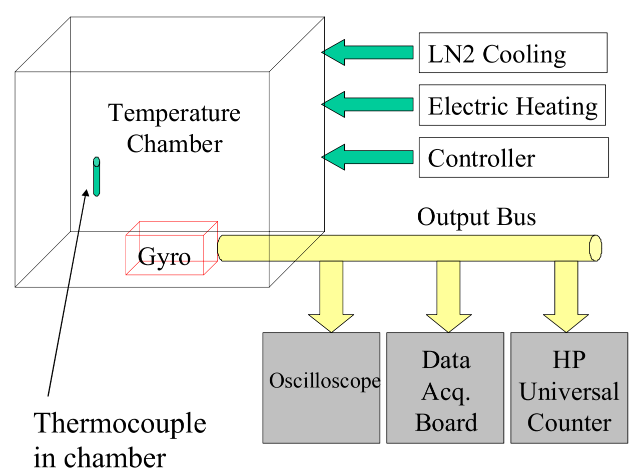

Figure 3. The conceptual diagram of the experimental setup. Cooling is done with liquid nitrogen.

3. EXPERIMENT SETUP

The temperature tests were performed on a packaged gyroscope using a temperature chamber under no rotation. Temperature regulation was performed by the temperature controller using electric heating and liquid nitrogen cooling. A diagram of the experimental setup is shown in Figure 3.

The figure shows the packaged gyroscope (PRG #105) placed along with supporting electronics into the temperature chamber. The control and signal outputs are connected though slip-rings to various instruments to measure voltage, frequency, etc. The temperature of the gyroscope is measured using the air temperature of the chamber through thermocouples read by the temperature controller. Fans mounted inside the temperature chamber ensure uniform air temperature inside the chamber.

The gyroscope is not rotating for the experiment. The temperature of the chamber is ramped up from 35°C to 65°C and down again at 5°C intervals. During the test period, both analog and digital data were recorded. The analog data were recorded with a National Instruments CB-68LP. The analog signals recorded were:

1. Rate output: DC Bias voltage proportional to the rotation rate of the gyroscope. In the case of no rotation, this is the zero rate offset (ZRO).

2. Gyroscope drive resonance frequency: Measured using LabView software to extract frequency.

3. Gyroscope sense resonance frequency

4. Automatic Gain Control (AGC): DC Bias indicating the force required to keep the amplitude of the drive signal constant.

The digital signals were recorded using a universal counter HP 53131A. The signals recorded were:

1. Drive resonance frequency,

2. Sense resonance frequency

3. Sense signal amplitude

For a single 5°C interval, the change in the sensitive parameters can be seen in Figure 4. The temperature plot shows the temperature inside the chamber rapidly increasing and stabilizing to 40°C in a number of minutes. Therefore, it can be assumed that the temperature inside the chamber is

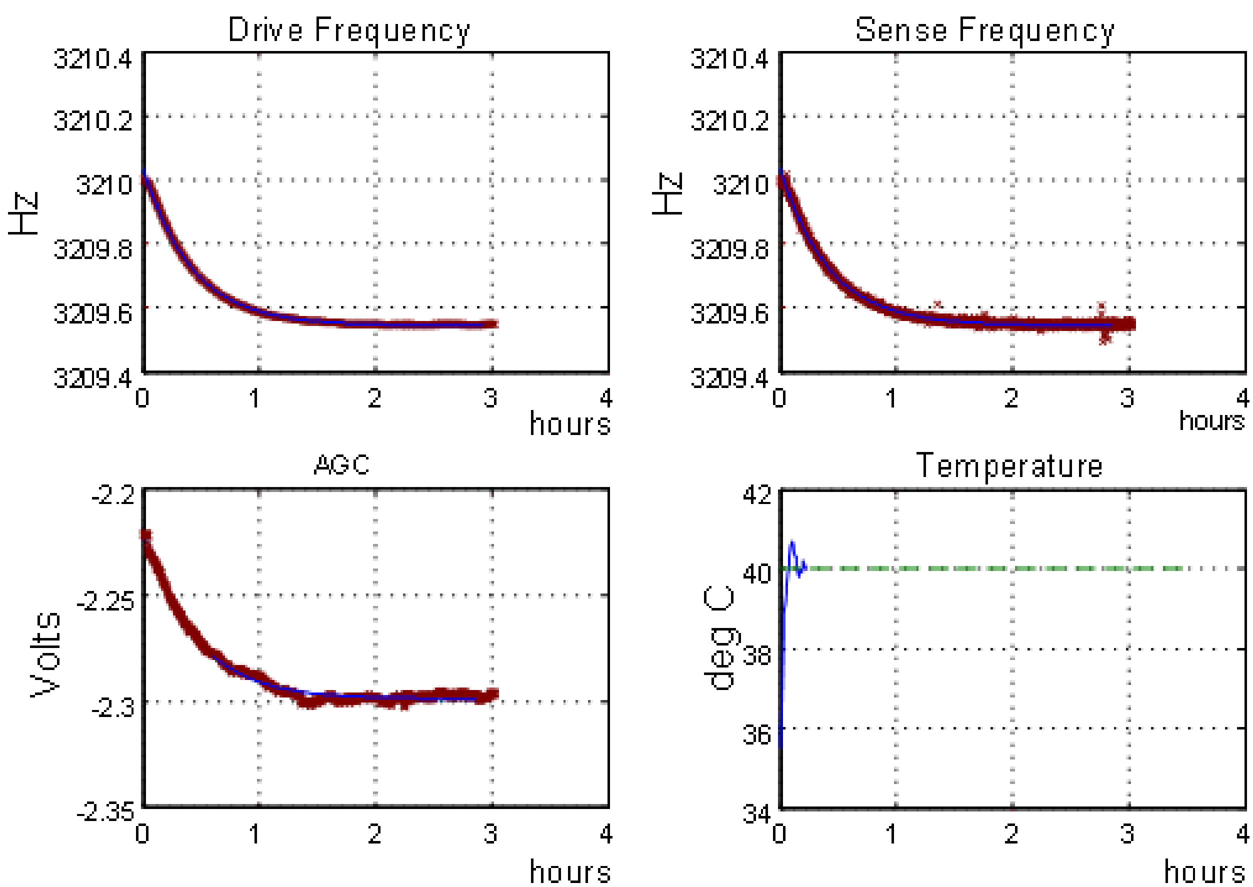

Figure 4. The response of the drive frequency, sense frequency, AGC voltage, and chamber temperature as a function of time for the increase in temperature from 35°C to 40°C.

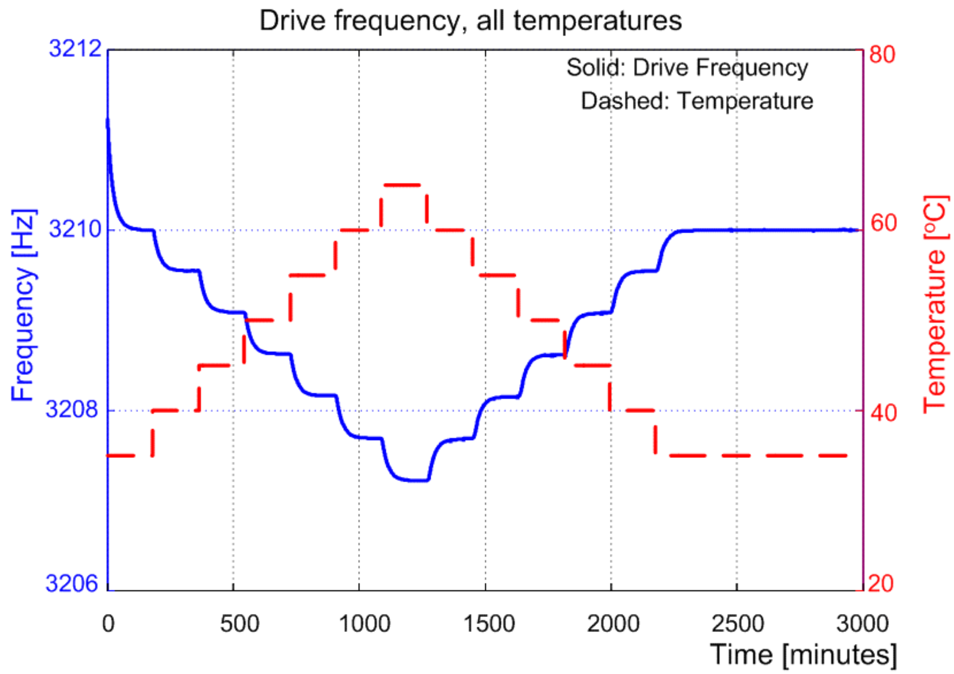

Figure 5. The response of the drive frequency on the left axis and chamber temperature on the right axis versus time for an entire experiment run.

35°C before t = 0 and becomes 40°C after t = 0. The response of the three outputs is clearly exponential decay. Stabilization of the outputs occurs two hours after temperature change. The long time delay is primarily due to the large heat capacity and low thermal conductivity of the vacuum package within which the gyroscope resonator resides.

An example of an entire experimental run is shown in Figure 5. In the figure the response of the drive frequency on the left axis and chamber temperature on the right axis versus time for the entire experiment. Plots of the sense frequency and AGC voltage versus time yield similarly shaped plots. The response of drive frequency to each change in temperature is similar to those described and shown in Figure 4 and can be described by the equation:

$f(t) = A+B*\exp(-t/\tau)$ (Equation 1)

where f is an output of the gyroscope, in Volts for AGC voltage and in Hz for drive frequency and sense frequency, t is the time elapsed after temperature change and τ is the time constant. A fit was applied to each of the segments in Figure 5 and the time constant was determined to be τ=0.42. The A and B parameters correspond to the final frequency at each temperature and a linear scaling constant, respectively. The stabilized AGC voltage and frequency are plotted in Figure 6. The lines represent heating and cooling during a single experimental period. From this figure, AGC voltage varies linearly at 13mv/°C while drive and sense frequency vary linearly at 93mHz/°C, confirming results obtained earlier by Peay (unpublished) and Shcheglov [2]. Furthermore, the lines overlap and suggest no hysteresis for AGC voltage, drive frequency, and sense frequency over the temperatures measured.

SUMMARY AND DISCUSSION

In summary, the accuracy of the JPL MEMS gyroscope under temperature was investigated. The following results were obtained:

·AGC voltage, drive frequency, and sense frequency respond in exponential decay fashion after experiencing a temperature change. While this is expected, the time constant is exceedingly large and indicates that if the gyro undergoes temperature cycling on the order of a few hours, there will need to be a correction factor added based on the history of the temperature. This temperature lag is in contrast with previous published results [2] and suggests that the packaging used in the newer version acts as a large temperature reservoir. Mitigation of this will come in the form of a temperature sensor that is able to track the temperature of the gyro itself, perhaps by being in a similar package located near the gyroscope. This also suggests that future research might determine if there is a temperature effect which depends on which axis is being driven versus being sensed.

The stabilized AGC voltage, drive frequency and sense frequency after temperature change is non-hysteretic and is strongly linear with temperature and with calibration can be used to indicate temperature of the gyroscope, as was expected from the previously published results.

Future experiments should be conducted to increase the temperature range and to determine the effect of temperature changes to a rotating gyroscope, which was not possible during this study due to an electrical failure with the module.

7. ACKNOWLEDGEMENTS

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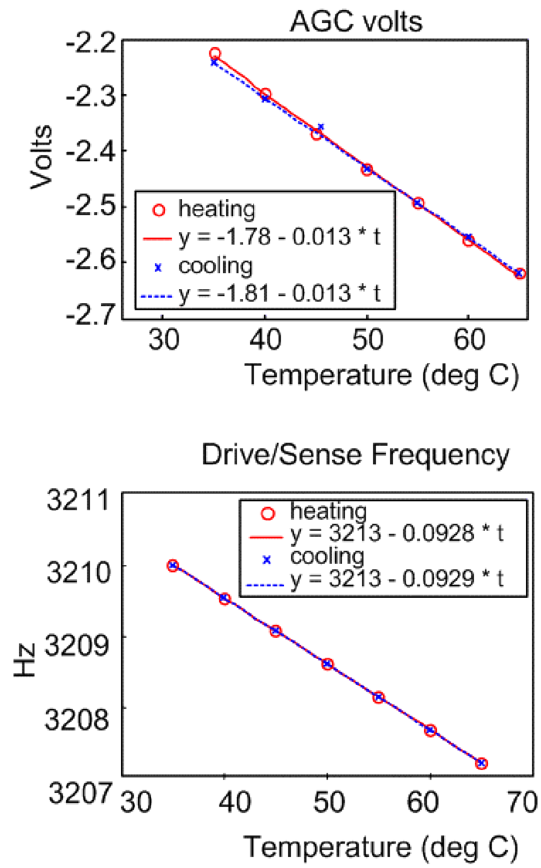

Figure 6. A plot of the stabilized AGC Voltage and the frequency for both Drive and Sense, which are statistically identical.

REFERENCES

[1] Bae SY. Hayworth KJ. Yee KY. Shcheglov K. Wiberg DV, "High Performance MEMS Micro-Gyroscope." SPIE-Int. Soc. Opt. Eng. Proceedings of SPIE – the International Society for Optical Engineering, vol.4755, 2002, pp.316-24. USA

[2] Shcheglov, K.; Evans, C.; Gutierrez, R.; Tang, T.K., "Temperature dependent characteristics of the JPL silicon MEMS gyroscope", Aerospace Conference Proceedings, 2000 IEEE, Volume: 11, 18-25 March 2000 Pages:403 - 411 vol.1

[3] Weinberg, J. Bemstein, S. Choy A. T. King, A., Kourepenis, and P. Maciei, "A Micromachined Comb-Drive Tuning Fork Rate Gyroscope," Proceedings of the 49th Annual Meeting "Future Global Navigation and Guidance, " The Institute of Navigation, June 21-23, 1993.

[4] Kourepenis A, Bernstein J, Connelly J, Elliott R, Ward P, Weinberg M. "Performance of MEMS inertial sensors", in *Proceedings IEEE 1998 Position Location and Navigation Symposium*, IEEE. 1998, pp.1-8. New York, NY, USA.

[5] Bernstein J. An overview of MEMS inertial sensing technology. Sensors (Peterborough, Nh), vol.20, no.2, Feb. 2003, pp.14-21. Publisher: Advanstar Communications, USA.

[6] Lefevre, H.C., Bourbin Y., Graindorge P., Arditty H.J., "Review of fiber optic gyroscopes", *Proceedings of SPIE the international society for optical engineering* [0277-786X] Lefevre, yr: 1983 vol: 369 pg: 386.

[7] D. Keymeulen, et al., "Tuning of MEMS device using Evolutionary Computation and open-loop Frequency Response Applied to the JPL MEMS microscopic gyro", in Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, March 2005.

[8] M. I. Ferguson, et al., "A Hardware Platform for Tuning of MEMS Devices Using Closed-Loop Frequency Response", in Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, March 2005.

[9] R. J. Terrile, et al., "Evolutionary Computation Technologies for Space Systems", in Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, March 2005.

BIOGRAPHY

Michael I. Ferguson is a member of the Technical Staff in  the Bio-Inspired Technologies and Systems group. His focus is on evolutionary algorithm application to VLSI design and arithmetic algorithms. He is currently working on the application of GA to tuning MEMS micro gyros. His other projects include evolution of digital and analog circuits intrinsically and extrinsically using a variety of methods. He was the Local Chair of the 2003 NASA/DoD Conference on Evolvable Hardware. He received a M.S. in Computer Science from University of California at Los Angles and a B.S. in Engineering Physics from the University of Arizona. Michael is a member of the IEEE.

Didier Keymeulen received the BSEE, MSEE and Ph.D. in  Electrical Engineering and Computer Science from the Free University of Brussels, Belgium in 1994.. In 1995 he was the Belgium laureate of the Japan Society for the Promotion of Science Post Doctoral Fellowship for Foreign Researchers. In 1996 he joined the computer science division of the Japanese National Electrotechnical Laboratory as senior researcher. Since 1998, he is member of the technical staff of JPL in the Bio-Inspired Technologies Group. At JPL, he is responsible for the applications of the DoD and NASA projects on evolvable hardware for adaptive computing that leads to the development of fault-tolerant electronics and autonomous and adaptive sensor technology. He served as the chair, co-chair, program-chair of the NASA/DoD Conference on Evolvable Hardware. Didier is a member of the IEEE.

Chris Peay is an Engineer affiliated with NASA's Jet  Propulsion Laboratory. He is currently the electronics, control, and testing lead of the JPL MEMS gyroscope development team, which he has been part of for more than 2 years. Prior to joining the JPL gyro team, Chris gained 10 years experience in electronics and computer engineering, primarily in communications, software engineering, and semiconductors. He received the BS degree in Electrical Engineering from the University of Utah and is pursing the MSECE degree at the Georgia Institute of Technology.

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Daliang Leon Li is currently pursuing a B.S. in electrical  engineering at the University of Pittsburgh in Pittsburgh, PA. His experiences include research in MEMS technologies, diblock co-polymers, ionic polymer metal composites (IPMC), and software engineering in SQL database technology. Daliang is a recipient of the University of Pittsburgh Chancellor's Scholarship, National Merit Scholarship, and was honored in the National Dean's List in 2003.